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The potential carbon neutrality of sustainable viticulture showed through a comprehensive assessment of the greenhouse gas (GHG) budget of wine production

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ABSTRACT

Sustainable agricultural and food processing practices are often proposed as attractive strategies enabling food systems to respond to the challenges posed by climate change in terms of adaptation and mitigation. However, information on the actual contribution to climate change provided by sustainable food production systems is lacking in literature.

With the intention to contribute to a more informed debate, this study aims at quantify the actual impact on climate of sustainable practices applied to a grape-to-wine system in Italy. The overall budget of greenhouse gas (GHG) fluxes is assessed at wine farm level, from the vineyard to the final bottle of wine, through an integration of methods, including the eddy covariance technique, the life cycle assessment (LCA) and the IPCC guidelines. All the components of the GHG budget have been considered: the (a) biogenic GHG fluxes and the (b) anthropogenic GHG emissions generated for the grape production as well as the (c) carbon stock change due to the vineyard management and the (d) anthropogenic GHG emissions generated by the transformation of grape into wine.

At the vineyard level, the overall GHG budget resulted to be close to zero, showing a potential carbon neutrality of sustainable viticulture: the sum of biogenic GHG fluxes (a) and the carbon stock change (c) resulted in a net carbon sink with a potential contribution to climate change mitigation of $-0{,}27 \pm 1{,}11$ Mg CO_2eq year^{-1} per hectare; while the anthropogenic GHG emissions (b) for the sustainable vineyard management accounted for $0{,}24 \pm 0{,}05$ Mg CO_2eq ha^{-1} year^{-1}.

The total carbon footprint (b + d) of sustainable wine is 0,79 ± 0,14 kg CO_2eq per bottle, with 15% attributable to the agricultural phase and 85% to the transformation of grape into wine.

These findings indicate that sustainable wine production has in general a lower contribution to climate change. In particular, sustainable practices applied to viticulture can turn the system into a net carbon sink able to totally compensate the anthropogenic emissions for the vineyard management. Therefore, sustainable viticulture allows food production with a potential carbon neutrality without exacerbating climate change.

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1. Introduction

Viticulture is a relevant and widespread agricultural system of the rural landscape with more than 7 million of hectares in the world, half of which are concentrated in Europe (FAOSTAT, 2018), where Italy, France and Spain represent the main wine producers with an average annual production of about 130 million hectoliters of wine (OIV, 2018a). Moreover, the cultivation of vineyards is expanding also outside the traditional wine-growing areas of Europe with the "new world wine producers" Argentina, Chile, California and United States, New Zealand, Australia, South Africa and China (FAOSTAT, 2018), as suitability for viticulture is changing under climate change (IPCC, 2014a; IPCC, 2014b; Bonfante et al.,

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2018) with potential new area becoming appropriate for viticulture. Furthermore, grape production and wine consumption are expected to increase following the projected growth of human population from 7.2 to 9.8 billion by 2050 (UN, 2017). However, it is worth noting that climate change is directly influencing the agricultural sector and will continue to affect also grape production. Even more frequent and intensive extreme events, such as droughts, floods and storms will lead also to changes in local weather patterns that will affect ecosystems with possible increase of plant diseases and competition for natural resources (IPCC, 2014a; IPCC, 2014b; FAO, 2017), compromising food security (FAO et al., 2017).

At the same time agriculture is one of the main contributors in terms of greenhouse gas (GHG) emissions causing global climate change, being responsible of approximatively one fifth of global emissions (IPCC, 2014c). In particular, intensive agriculture, with high levels of inputs, significantly impacts on the environment causing land degradation, deforestation, declines in biodiversity, depletion of soil, air and water pollution and high levels of greenhouse gas emissions (Mengel, 1993; McLaughlin and Mineau, 1995; IPCC, 2014a; IPCC, 2014b; Dudley and Alexander, 2017; Muhammed et al., 2018). Nevertheless, the rural landscape represents a multifunctional system (Winkler et al., 2017) able to provide a plethora of important economic, cultural and ecological services to the local communities and to the global system, including carbon sequestration. Vineyards in Mediterranean and temperate areas are potential good examples in particular for the latter service, as perennial agricultural crops can store carbon both in the permanent woody structures and in the soil (Kroodsma and Field, 2006; Williams et al., 2011; Scandellari et al., 2017), with a potential contribution to climate change mitigation. However, the intensive management of vineyards and of the grape-to-wine transformation system influence the GHG emissions of grape and wine production and can cancel out and even reverse the positive effects of carbon sequestration, with a potential opposite effect causing climate change.

Climate change has been identified as one of the key factors undermining food security and causing world hunger that is on the rise with an increase of undernourished people from 777 million in 2015 to 815 million in 2016 (FAO et al., 2017). In this regard, the main international agreements on climate as the Kyoto Protocol and the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), as well as the main Decisions and Regulations at European and national level, ask for concrete action for climate change mitigation and adaptation, also in the agricultural sector. Therefore, farming systems need to adjust requiring actions to both mitigate and adapt to climate change and to natural resource scarcities. In particular, the priority need for the world population should be to identify and foster agricultural practices that aim at increasing food security and can at the same time have climate change mitigation benefits.

Sustainable agriculture and food production seem to represent a possible solution to support food security and respond to the 2030 Agenda for Sustainable Development which encompasses the Paris Agreement under the UNFCCC and the Sustainable Development Goals (SDGs).

According to FAO (2017), a climate smart agriculture (CSA) should simultaneously tackle the challenges to sustainably increase productivity and incomes, build resilience to the impact of climate change and contribute to climate change mitigation. Moreover, organic farming has been recognized as a key strategy to address together climate change adaptation and mitigation, enabling also to maintain and improve the financial performance of agriculture sector (Sacchelli et al., 2017) as well as the productivity and quality of food. Organic farming can also have benefits in terms of protection of the biodiversity, due to a more robust balance between resource availability, living organisms and productivity, at the same time maintaining pests and diseases at the lowest level (Provost and Pedneault, 2016). Practices such as tillage and soil preparation have been historically applied in conventional agriculture (Triplett and Dick, 2008) or in other ecosystems such as forests (Hörnfeldt et al., 2012) to enhance new planting and soil productivity or for weed control. However, recent studies reviewed by Busari et al. (2015) demonstrated that no-tillage and the maintenance of grass cover in permanent crops can represent effective sustainable practices able to not negatively affect or even enhance productivity, while leading to several environmental and climate benefits. Also the crop residues management with reuse on soils can represents a resource in terms of organic fertilization, improving soil productivity and crop production and maintaining high levels of soil organic matter (Reicosky and Wilts, 2005; DeVetter et al., 2015; Cirigliano et al., 2017; Devi et al., 2017).

The food transformation process also plays a key role in terms of the overall sustainability of the food sector. In particular for the wine processing, the adoption of sustainable practices can consist in the application of product or process innovation, organic wine production process (according to the European regulation n. 203/2012), pollution prevention, and stewardship of natural resources (Berns et al., 2009; Carrillo-Hemosilla et al., 2010; Gilinsky et al., 2016).

Accordingly, sustainable agricultural practices and food processing (encompassing, but not limited to, organic farming and organic transformation of food products, and including in general reduced use of chemicals, reuse of crop residues for organic fertilization, no-till and grass cover in perennial crops for soil protection, energy efficiency strategies, and sustainable packaging) can best respond to the impacts of climate change, enabling food production systems to maintain a balance between productivity and environmental preservation. In this regard, there is a growing interest in the scientific community in understanding the nexus between agricultural production, environmental impact and climate change (Aydinalp and Cresser, 2008). Moreover, food consumers' awareness and education are increasing with a consequent growing willingness in consumption of healthy and organic food with less environmental impact (Barber et al., 2009; Agovino et al., 2017; Ricci et al., 2018), thereby sustainable agriculture has experienced a steady increase in European countries (Laureti and Benedetti, 2018) encouraged also by local to global policies (e.g. the European Common Agricultural Policy – EU CAP).

Flores (2018) underlines that many studies in literature provide useful assessments of the impacts of agriculture and food products on the environment and on climate but only a few identifies sustainable practices for food production and evaluates their impact on climate and environment, in particular for the wine sector (Marshall et al., 2010; Grimstad, 2011; Gilinsky et al., 2015, 2016). Furthermore, most of the existing studies consider the impacts of different phases of the food production process through the product's life cycle, but they often ignore ecosystem services provided by the agricultural systems, including carbon sequestration (Pizzigallo et al., 2008; Chiriacò et al., 2017). An integration of methods that may be potentially complementary is therefore favorable (Pizzigallo et al., 2008; Bosco et al., 2013) for a full and complete assessment of the impact on climate of sustainable agricultural practices and food processing.

In order to contribute to a better understanding of the actual impact of sustainable food production on the climate system, this study aims at quantifying the overall budget of the GHG fluxes of a sustainable grape-to-wine system. In particular, the study aims at assessing all the GHG emissions and removals occurring at wine farm level, through an integration of methods that quantify the

impact on climate of sustainable wine production in terms of GHG emissions and mitigation potential provided by carbon sequestration. The comprehensive GHG budget is therefore assessed in this study considering all the involved components, such as both the (a) biogenic GHG fluxes and the (b) anthropogenic GHG emissions generated for the grape production as well as the (c) carbon stock change due to the vineyard management. Moreover, for a complete assessment of the full grape-to-wine system, the study evaluates also the (d) anthropogenic GHG emissions generated by the grape transformation process into wine.

Hence, this study represents a good example for a comprehensive understanding of the overall GHG budget and of the consequent actual contribution to climate change of sustainable viticulture. Such kind of information provided by this study is of wide interest in the scientific community working with agrosystem and climate change and acquires great importance also for decision makers in the evaluation of the effect of agro-environmental measures of the Common Agricultural Policy (CAP) and in the framework of the reporting and accounting obligations under the UNFCCC and its Kyoto Protocol and the UE decision 529/2013.

2. Experimental site description

The GHG budget is assessed in this study in a sustainable wine farm that produces organic and high-quality wines. The farm is located in Italy in Castiglione in Teverina (Viterbo) in the northern part of the Lazio region (Central Italy). The study area is in the Vulsino volcanic apparatus of central Italy, where the geological formation consists in volcanoclastic deposits, predominantly ignimbrites composed by tuffs, lapilli and inconsistent ash. The soils are classified as Entisols, Xeropsamments group in Soil Taxonomy (USDA, 2010). They are slightly acidic and well drained as a consequence of the xeric moisture regime, texture and slight inclination of the ground (generally less than 5%). The climatic conditions are characterized by average annual precipitations of about 788 mm and average daily temperatures around 23.9 °C during the hottest month of July and around 5.5 °C during the coldest month of January (average data for the period 1982–2012, source: Climate-data.org).

The whole process of wine production is directly carried out in the farm, from the grape cultivation to the transformation into wine, till the packaging of the final bottles of wine (Fig. 1). The GHG budget is assessed at farm level considering the GHG emissions and removals occurred during the temporal framework of 12 months, corresponding to a productive year, from August 2014 to July 2015, including the grape harvesting of 2014 and the following field operations until the successive grape harvesting.

The vines of the grape variety Montepulciano (Violone) were 10 years old in 2014 and the vineyard is trained to a lateral cordon, spur pruned, with a plant density of 5.000 vines per hectare and planting distance of 2,5 between rows and 0,8 m between vines in the same row (Table 1).

Sustainable management practices are applied in the farm both in the field and in the cellar. The most relevant sustainable practices applied in the field are:

- reduced use of chemicals (limited amount of copper and sulphur allowed according to organic farming criteria – Reg. (EC) n. 834/2007 and Reg. (EC) n. 889/2008);
- no-till and grass cover for soil protection;
- removal from the field of the shredded pruning material so to avoid the spread of pests and diseases and reduce treatments;
- reuse of vineyard residues (pruning and grape residues) for compost production;
- application of on-farm produced compost for soil organic fertilizer.

The sustainable practices applied in the cellar include:

- reduced use of chemical inputs during vinification (according to the organic wine production process – Reg. (EU) n. 203/2012);
- electricity saving, thanks to the natural maintenance of temperature in the cellar that is dug into the rock;
- use of sustainable packaging solutions that include ultralight glass bottles (360 g) with 10% less of weight respect to standard bottles, considering that glass bottles usually represent the major source of GHG emissions in wine production (Iannone et al., 2016; Martins et al., 2018).

The grape harvest took place on the 5th October 2014 (Table 2) with a grape yield of 2,5 tons ha^{-1}. The grape yield was particularly low respect to the average values of 8–10 tons per hectare registered in Italy in the period 2000–2016 (OIV, 2018a; FAOSTAT, 2018) and considering the maximum yield of 13 tons per hectare allowed by the specifications for the production under the appellation of origin of the grape variety Violone (DOC “Colli Etruschi Viterbesi” o “Tuscia” - D.M. 30.11.2011 - G.U. 295 20.12.2011). The low yield is due to two main reasons. On one side, organic viticulture and high-quality wine production have a still general lower productivity, due to the limited use of chemical inputs and to the reduced number of buds as a result of pruning and training practices that lead to lower quantity of grape but with higher quality parameters (Döring et al., 2015; Dobrei et al., 2016). On the other side, unusual weather events occurred in central Italy in late spring 2014, with 100 mm of rain in May and 124 mm in June recorded by the farm weather station, respect to the average of 54 mm in May and 54 mm in June (average data for the period 1982–2012, source: climate-data.org). This led to extremely unfavorable conditions for viticulture: higher frequency and consistency of precipitations and the consequent wetter conditions favored pathogens outbreaks, while the few sun hours due to cloudiness slowed the vegetative vine development (Fregoni, 2013). However, this low level of yield registered in 2014, beside reflecting the likely ongoing effects of climate change that are projected also to worsen in the future (IPCC, 2014a; IPCC, 2014b; IPCC, 2014c), doesn't influence the analysis of the GHG budget that is conducted per unit of area (hectare). Rather, the assessment of the GHG budget considering lower yields, respect to average conditions, represents a conservative approach in which the impact in terms of anthropogenic GHG emissions (see section 4.3) is partitioned by a smaller amount of product (i.e. a smaller number of bottles produced) providing possibly higher emissions per unit of product, thus avoiding the risk of underestimation of emissions (IPCC, 2006).

The grape was manually harvested with the help of a tractor and a trailer for the transport of grapes to the cellar. The first field operation after the grape harvest took place in October 2014 and consisted of a mowing for weeds control between the vines under the row with the use of the tractor. The manual pruning and binding of the grape vines occurred in February 2015. In mid-April 2015 a mowing for weeds control between the rows was carried out with the use of the tractor. Another mowing with tractor for weeds control between the vines under the row occurred in the first half of May 2015, followed by a mowing for weeds control between the vine rows on June 2015. Weed residues from mowing are shredded and leaved on the soil, while the vines pruning material is shredded and collected to be composted in the farm, together with the grape residues (stalks, grape skin and grape seeds) resulting from the vinification, and re-used on farm as organic fertilization of the soil. The compost produced from the vineyard residues is then

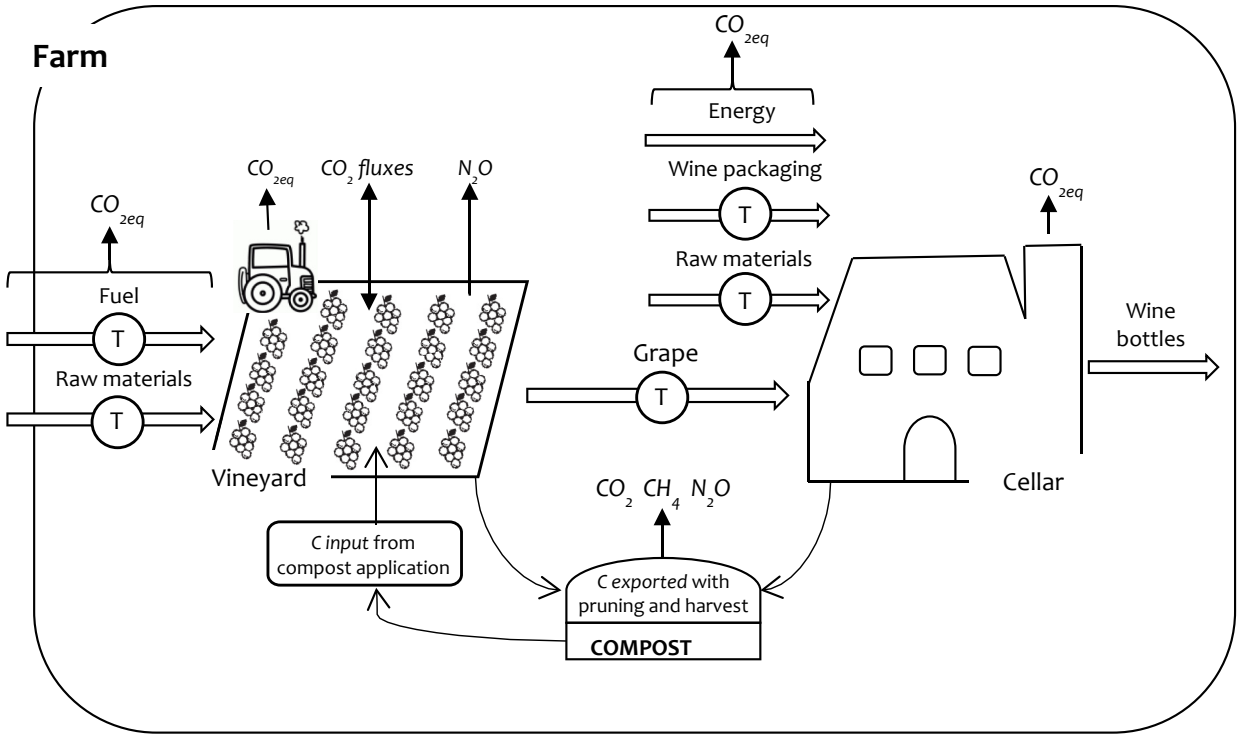

Fig. 1. Breakdown of the components contributing to the total GHG budget at farm level, including the agricultural phase and the transformation process (vinification, bottling and packaging).

Table 1
Characteristics of the vineyard system (Data source: farm registry).

	Values
Vineyard age (years)	10
Vine plants (n ha^{-1})	5.000
Grape yields (ton/ha^{-1})	2,5
Wine production (L ha^{-1})	1.500
Bottles of wine of 0,75 L (n ha^{-1})	2.000

Table 2
Annual operations for the agronomic management of the vineyard system for the period 2014–2015 (Data source: farm registry).

Field operations	Period
Grape harvesting	5th October 2014
Mowing for weeds control under the row	October 2014
Manual pruning and binding of the grape vines	February 2015
Pruning shredding and collection	March 2015
Mowing for weeds control between the rows	mid-April 2015
Mowing for weeds control under the row	May 2015
Mowing for weeds control between the rows	June 2015
Four treatments for pests' control	May–July 2015

distributed on-farm under the row with the aim of fertilizing the soil, limiting the spread of weeds and reducing soil erosion (DeVetter et al., 2015; Cirigliano et al., 2017). No irrigation occurs and no chemicals for fertilization or weeds control are applied, with the exception of limited amounts of copper oxide and sulphur for pests' control, according to the organic farming criteria (Reg. (EC) n. 834/2007 and Reg. (EC) n. 889/2008). Four treatments with a total amount of 1,75 kg ha^{-1} of copper oxide and 1,60 kg ha^{-1} of Sulphur were carried out between May and July 2015 (Table 2).

The transformation process of the grape into wine is carried out directly in the cellar and it starts immediately after the grape harvest. It includes the vinification, the bottling and the packaging of the wine, with a total production in 2014 of 1.500 L of wine per hectare, corresponding to 2.000 bottles of wine of 0,75 L per hectare (Table 1). The organic wine production process implies the minimum use of chemical inputs as possible according to the Reg. (EU) n. 203/2012 on the organic wine production. Moreover, the cellar, that is north-west exposed and dug into the rock, takes advantages from the natural damping of the outside temperature with consequent reduced energy consumption for electricity and lower GHG emissions for the temperature maintenance that is fundamental for the wine fermentation process (Ribereau-Gayon et al., 2006).

Furthermore, the use of ultralight glass bottles for the packaging implies a further reduction of anthropogenic GHG emissions, being the glass bottles one of the main contributors of GHG emissions in the wine making process (Iannone et al., 2016; Martins et al., 2018).

The grape residues of the vinification process (stalks, grape skin and grape seeds) are collected to be composted in the farm together with the pruning material and re-used as organic fertilization of the soil. At the end of the wine production process for the period 2014–2015 about 4 tons ha^{-1} (fresh weight) of final compost were produced by the vineyard residues, of which about 3,1 tons ha^{-1} (fresh weight) resulting from the annual pruning material and 0,9 tons ha^{-1} (fresh weight) of grape residues resulting from the vinification.

3. Methodology to assess the comprehensive GHG budget

The GHG fluxes of agroecosystems can represent either an emission or a removal to and from the atmosphere; therefore, the GHG contributions to the total budget can have positive or negative sign. For the purpose of this study, a positive (+) sign indicates an emission to the atmosphere, while a negative (−) sign represents a removal from the atmosphere. The GHG budget is calculated as the

algebraic sum of GHG emissions and removals occurring during a productive year, from August 2014 to July 2015 (12 months), including the grape harvesting of 2014 and the following field operations. The GHG budget is assessed at farm level including the field phase for the cultivation and management of the vineyard system as well as the transformation process of grape into wine (Fig. 1).

The total GHG budget from the vineyard system up to the wine production (GHGw) is calculated (Eq. (1)) as the sum of the (a) biogenic GHG fluxes (F_{BIOG}) and (b + d) anthropogenic (E_{ANTR}) GHG emissions, including CO_2, CH_4 and N_2O, and the (c) carbon stock changes in the vineyard due to the agronomic operations for the field management (F_{MG}).

The GHG fluxes are assessed differently depending on the gas and its origin: biogenic vineyard–atmosphere fluxes of CO_2 (i.e. net ecosystem exchange - NEE) are measured using eddy covariance (EC) technique; other biogenic emissions of CO_2, N_2O and CH_4 are calculated applying the methodologies developed by the Intergovernmental Panel on Climate Change (IPCC); anthropogenic emissions of the three GHGs due to the productive process are estimated via a life cycle assessment (LCA) from the vineyard to the bottle of wine; while the annual carbon stock changes due to the agronomic management were assessed by direct measurements.

$$GHG_W = F_{BIOG} + F_{MG} + E_{ANTR} \quad (1)$$

where:

$$F_{BIOG} = F_{CO2(EC)} + F_{CO2(C)} + F_{CH4(C)} + F_{N2O(C)} + F_{N2O(S)} \quad (2)$$

and

$$F_{MG} = F_S + F_G + F_{PB} \quad (3)$$

and

$$E_{ANTR} = E_{Field} + E_{Cellar} \quad (4)$$

Eq. (2) asses the (a) biogenic GHG fluxes (F_{BIOG}) in the vineyard, where $F_{CO2(EC)}$ represents the biogenic CO_2 vineyard–atmosphere fluxes measured with the EC technique, while $F_{CO2(C)}$, $F_{CH4(C)}$, $F_{N2O(C)}$ and $F_{N2O(S)}$ represent the biogenic emissions of carbon dioxide, methane and nitrous oxide from on-farm compost production and soil management calculated according with IPCC (2006).

Eq. (3) calculates the (c) carbon stock changes in the vineyard due to the agronomic operations for the field management (F_{MG}), where F_S represents the organic carbon added to the soil organic carbon (SOC) stock through the annual soil organic fertilization with compost produced on farm by agricultural wastes. F_G is the carbon removed with the harvested grape, while F_{PB} is the carbon removed with the pruning of biomass.

Eq. (4) assess the (b + d) anthropogenic GHG emissions (E_{ANTR}), where E_{Field} represents the anthropogenic GHG emissions coming from the field operations for the management of the vineyard, while E_{Cellar} represents the anthropogenic GHG emissions coming from the transformation process of grape into wine (including vinification, bottling and packaging), both assessed with a LCA approach.

The total GHG budget of the vineyard system up to the wine production is expressed in CO_2 equivalent (CO_2eq) according to the global warming potential (GWP) emission factors with a time horizon of 100 years (Myhre et al., 2013) which assigned 1 GWP to 1 kg of CO_2, 28 GWP to 1 kg of CH_4 and 265 GWP to 1 kg of N_2O.

3.1. Biogenic fluxes of GHGs

The biogenic GHG fluxes related to the vineyard system include the vineyard–atmosphere exchanges of biogenic CO_2 fluxes. Moreover, for a comprehensive GHG assessment of the farm system, the biogenic emissions of carbon dioxide, methane and nitrous oxide due to the compost production process and the soil management following the compost distribution are included in the calculation (F_{BIOG} - Eq. (2)).

The three GHGs included in the budget (CO_2, CH_4, N_2O) have been calculated with different techniques depending on their origin. Fluxes of CO_2 ($F_{CO2(EC)}$ in Eq. (2)) to and from the whole ecosystem (soil + vegetation, i.e. the net ecosystem exchange - NEE) have been measured in the field using the eddy covariance (EC) methodology. Other CO_2, CH_4 and N_2O biogenic emissions from compost production ($F_{CO2(C)}$, $F_{CH4(C)}$, $F_{N2O(C)}$ in Eq. (2)) and soil management ($F_{N2O(S)}$ in Eq. (2)) instead have been assessed using the IPCC methodologies (IPCC, 2006), as no direct measurements were available.

3.1.1. Eddy covariance measurement for biogenic CO_2 fluxes

The EC technique allows the calculation of on-site fluxes of gases to and from the whole ecosystem (soil + vegetation, i.e. the net ecosystem exchange - NEE) via the covariance between its entity and vertical wind velocity. High frequency measurement of these and other complementary variables are performed using an ultrasonic anemometer and a fast-response gas analyser (see Aubinet et al., 2012 for further details on the technique). The EC setup in the investigated vineyard system consisted of a sonic anemometer Gill WindMaster (Gill, Lymington, UK) and an open-path infrared gas analyser (LI-7500, LICOR, Lincoln, NB, US). The additional instrumentation included a weather station for measuring air temperature, air pressure, air humidity and other relevant meteorological variables. Data were collected at a frequency of 10 Hz, and then processed using EddyPro software from LICOR. The fluxes were calculated on a 30 min period, and the most important corrections were carried out including coordinate rotations of the sonic anemometer data, time-lag compensation, low and high frequency spectral corrections (see Aubinet et al., 2012).

Moreover, the half-hourly time series of CO_2 flux were further corrected for storage component, quality checked, de-spiked and filtered based on calm conditions (u^*), applying a combination of two approaches: (i) as described in Papale et al. (2006) and in Reichstein et al. (2005); (ii) as reported in Barr et al. (2013). The NEE values falling in the median (50^{th} percentile) were considered, with a range of uncertainty of NEE values filtered by 5th and 95th percentile of the distribution of u^* thresholds values. The filling of data gaps resulting from the filtering of the time series was performed according to Reichstein et al. (2005). The final time series was then aggregated to daily, monthly and annual time scales.

3.1.2. Other biogenic CO_2, CH_4 and N_2O emissions

3.1.2.1. Biogenic emissions from compost production. The composting of the vineyard residues is an aerobic process in which, according to IPCC (2006, vol. 5 ch. 4), a large fraction of the degradable organic carbon is usually converted in CO_2. However, a few amounts of methane are formed in anaerobic sections of the compost, albeit it is oxidized to a large extent in the aerobic sections of the compost, and some N_2O emissions are produced as well (IPCC, 2006, vol. 5 ch. 4). At the end of the wine production process for the period 2014–2015 about 4 tons ha^{-1} (fresh weight) of compost derived by on-farm organic residues were applied in the field as organic fertilization (see section 2). Thus, to asses CH_4 and N_2O emissions from the compost production process ($F_{CH4(C)}$ and $F_{N2O(C)}$ in Eq. (2)), the Tier 1 approach of IPCC (2006, vol. 5 ch. 4) was

applied for the purposes of this study using the default average emission factor of 4 g CH_4 and 0,24 g N_2O per kg of fresh compost, as proposed by IPCC (2006).

The CO_2 emissions resulting from the aerobic fermentation due to the compost production ($F_{CO2(C)}$ in Eq. (2)) has been estimated considering the difference between the amount of carbon found in the mature compost (corresponding to the 43 ± 2,1% of the dry matter with 70% humidity, as derived by laboratory analysis) respect to the initial carbon contained in pruning and grape residues (see section 3.2.1), at the net of the carbon already counted in methane emissions from the compost production process.

3.1.2.2. Biogenic emissions from soil management. The direct and indirect N_2O emissions from the compost application to soil for fertilization ($F_{N2O(S)}$ in Eq. (2)) were estimated with a Tier 1 approach according to IPCC (2006). The N content of the compost was calculated by laboratory analysis and corresponds to 2 ± 0,2% of the total dry matter that was assessed to be the 30% of the fresh weight. Therefore, the compost incorporation implies a total N input to the soil of 25 kg N ha^{-1}. We calculated direct emissions of N_2O from decomposition and mineralization of compost using the default value (EF_1) of 0,01 for the equation 11.1 as reported by IPCC (2006). Indirect N_2O emissions from atmospheric deposition of N volatilized from the compost use were calculated applying the default value of 0,2 (IPCC, 2006) for the fraction of the applied N fertilizer contained in the compost that volatilizes as NH_3 and NO_x and the emission factor for N_2O emission from N atmospheric deposition (EF_4) of 0,01 as reported for the equation 11.9 by IPCC (2006). Indirect N_2O emissions from leaching were calculated using the default value of 0,3 (IPCC, 2006) to estimate the fraction of N contained in the compost applied to the vineyard managed soil that is lost through leaching and runoff and applying the default emission factor (EF_5) of 0,0075 as indicated for the equation 11.10 by IPCC (2006).

Methane fluxes from soil are usually related to high concentrations of water in the soil (IPCC, 2006; Tate, 2015), thus methane emissions from soil due to the compost application for soil fertilization were assumed to not occur, considering that the investigated vineyard is not irrigated.

3.2. Annual carbon stock changes due to the agronomic management

The agronomic management of the vineyard implies field operations that can influence the annual carbon stock changes of the vineyard system (F_{MG} - Eq. (3)). In particular, the compost application under the rows implies an increase of the SOC content, while the pruning of biomass as well as the grape harvest implies a loss of carbon from the system.

3.2.1. Carbon loss from grape harvest and pruning of biomass

A certain amount of carbon accumulated by the vines during the summer is partitioned into fruit and annual vegetation and is annually removed from the vineyard system with the pruning of biomass and the grape harvest and then released as part of the wine fermentation process. This component is not tracked in the calculation of NEE (Longbottom and Petrie, 2015). Therefore, for a comprehensive GHG accounting of the vineyard system these carbon stock variations due to the agronomic management should be quantified and deducted from the GHG budget.

The carbon removed with the grape harvest in October 2014 (F_G in Eq. (3)) was calculated in two different ways for the grape juice and the other grape components (stalks, grape skin and grape seeds). Considering the annual wine production of 1.500 liters ha^{-1}, the carbon content of the grape juice was calculated by means of the Brix degrees in the wine must (derived by laboratory analysis) and the molecular weight of the sugar components (Ribereau-Gayon et al., 2006; OIV, 2018b). Whereas, an average moisture content of 80% on fresh weight (as derived by laboratory analysis) and a carbon content of 47% on the dry matter (IPCC, 2006 vol 4 ch. 4) were considered to assess the carbon loss from the 0,9 ± 0,2 tons ha^{-1} of grape residues directly measured as resulting from the vinification process (see section 2).

The carbon removed with the pruned biomass in February 2015 (F_{PB} in Eq. (3)) was directly measured in the field by weighing representative samples of pruning residues form different vines. The pruned biomass was equal to 3,1 ± 0,76 tons ha^{-1} (fresh weight). A sub-sample was then exsiccated at 65 °C in a forced-air oven to constant weight according to Keller and Koblet (1995) to assess the dry matter (54% humidity) and calculate the carbon loss, considering the carbon content 47% of dry matter (IPCC, 2006).

3.2.2. Increase of SOC from compost application

The application of compost to the vineyard, besides representing a substitute for synthetic fertilizers, may entail a significant increase in soil carbon sequestration (Favoino and Hogg, 2008; Mondini et al., 2007). In fact, the application of on-farm produced compost implies a return to the vineyard system of a fraction of the organic carbon previously subtracted with the grape harvest and the pruning of biomass. Part of the organic carbon contained in the compost annually added to the vineyard is emitted in atmosphere as CO_2 through the soil respiration and is already measured with the EC technique (see paragraph 3.2.1), while another part remains in soil inducing an increase in the SOC stock of vineyard system (F_S in Eq. (3)), as observed also by Ren et al. (2017). The application of on-farm produced compost to the vineyard is annually performed since the planting of the vines (2004), with about 4 tons ha^{-1} (fresh weight) per year of compost for the period 2014–2015 (see section 2). However, the SOC stock variations related to management practices, including the compost application, occur with non-linear dynamics during the following 20 or more years (IPCC, 2006; Chiti et al., 2018). Therefore, a spot measure on a yearly basis of the SOC stock change would not be representative, rather a long-term trend of SOC increase attributable to the compost application should be considered to extrapolate the average annual rate. For this reason, no soil samples were directly analyzed to assess the SOC increase, whereas the main existing literature has been reviewed to derive an average annual rate of SOC increase from compost application (Triberti et al., 2008; Bos et al., 2017; Freibauer et al., 2004; Lou and Nair, 2009).

3.3. Anthropogenic emissions of GHGs

The field operations for the agronomic management of the vineyard and the transformation process in the cellar of grape into wine imply the production of a certain amount of anthropogenic GHG emissions (E_{ANTR} - Eq. (4)).

The overall anthropogenic GHG emissions associated with the production process across its overall life cycle, also known as the carbon footprint (CF), were assessed via a LCA applied with a "cradle to gate" approach (Finkbeiner et al., 2006): the production and transport of raw materials, the field operations, the transformation process in the cellar from grape to wine and the packaging of the final bottle of wine were included in the boundary system (Fig. 1).

The methodology we adopted follows the ISO 14040 standard on "LCA - Principles and procedures" and the ISO 14044 on "LCA - Requirements and guidelines" (Finkbeiner et al., 2006). The data were processed by the LCA software SimaPro 7.3.3.

The data used to perform the LCA refers to the overall wine

making process for the period 2014–2015 and were directly collected on site from invoices, registries, measures and archives of the farm (see Table 4, Table 5 and Table 6). Only when primary data were not available, conservative data were derived from literature and international databases which support environmental assessments (i.e. Ecoinvent database) or calculated using appropriate models (IPCC, 2006). Table 3 summarizes the main emission factors used in this study.

The CF left by human activities for the grape cultivation and the wine production was assessed considering as functional unit (FU) the unit of product (1 bottle of wine of 0,75 L, FU_{Bottle}) and the unit of land (1 ha of vineyard, FU_{ha}). The choice to use the two different FUs in this study rests on two reasons. On one side, a land-based GHG accountability system for the assessment of the CF of products or processes whose life cycle involves the land use of managed ecosystems, would be more comprehensive than the CF assessment based solely on the unit of product. In fact, as demonstrated by different studies in literature (Renzulli et al., 2015; Chiriacò et al., 2017), the CF assessed by product units for agricultural products is not always fair: the CF per units of agricultural products is much related to the yields, while more intensive management, with higher intensity in the use of agricultural inputs per hectare, generates higher GHG emissions in absolute terms per unit of land, that can be overshadowed by the higher productivity when assessing the CF per units of product. This highlights the need to identify an appropriate FU - or, better, several FUs, including the land area functional unit - to assess the environmental impacts of crops, as occurred in many studies in literature (Charles et al., 2006; Harada et al., 2007; Kavargiris et al., 2009; Ferng, 2011; Litskas et al., 2011; Nalley et al., 2011; Michos et al., 2012; Notarnicola et al., 2012; Roer et al., 2012; Zafiriou et al., 2012; Eshun et al., 2013; Hayashi, 2013; Murphy and Kendall, 2013; Meier et al., 2015). On the other side, the CF assessed per unit of land (FU_{ha}), in addition to the unit of product (FU_{Bottle}), allows a direct comparison with the carbon stock changes due to agronomic operations and the biogenic GHG fluxes of the vineyard system, that are directly measured or assessed per unit of land (hectare) through the eddy covariance (EC) technique or with the IPCC methodology. Thus, the use of the two FUs permits a more effective and comprehensive assessment of the real contribution to climate change of the entire agrosystem and increases the relevance of the LCA.

The LCA applied in this study follows an attributional approach where the environmental impacts in terms of GHG emissions are quantified and allocated in relation to the life cycle of the sustainable production process. However, the comparison of the attributional LCA applied to the sustainable production in this study with other LCA results from conventional systems in literature allows for a potential consequential LCA approach, where it is possible to appreciate how the environmental impacts in terms of GHG emissions will change in response to possible decisions (i.e. organic/sustainable vs conventional practices applied to vineyards).

3.3.1. Anthropogenic GHG emissions from the vineyard

All the field operations described in section 2 and summarized in Tables 1 and 2 were considered to assess the CF at the vineyard level (E_{Field} in Eq. (4)). The production, packaging and transport of raw materials, such as copper oxide and sulphur, iron yarns for binding and fuel for the agricultural operations, were also included in this phase, as well as the transport of the grape to the cellar (Tables 4 and 6).

Furthermore, as the vineyard is on a land which has been used for agricultural purposes for longer than 25 years, we didn't consider the GHG emissions from land use change, according to ISO 14040 and ISO 14044 (Finkbeiner et al., 2006) and IPCC (2006). For the same reason, also GHG emissions related to the operations for the initial establishment of the vineyard were not included as the life time is expected to be longer than 25 years (Finkbeiner et al., 2006).

The GHG emissions from the vineyard were allocated respect to raw materials. Allocation assigns a proper share of environmental impacts according to how much the analyzed products cost or weight respect to the total production (Notarnicola et al., 2015; Palmieri et al., 2017). Allocation can be performed through different methods ranging from economic allocation (based on market prices and applied mainly when the system generates co-products or byproducts that are sold in the market) to mass allocation (that considers the quantitative aspects of the productions). A mass allocation was applied in this case to the amount of paper used for the packaging of copper oxide and sulphur in relation to the amount of copper oxide and sulphur used for the production of 1 bottle of wine (FU_{Bottle}).

3.3.2. Anthropogenic GHG emissions from the transformation process in the cellar

The CF of the transformation process in the cellar (E_{Cellar} in Eq. (4)) includes the vinification, the bottling and the packaging of the final wine. The total energy required in the cellar for the transformation process is 0,66 kW per liter of produced wine (Table 5)

Table 3
Emission factors.

Input	Unit	Emission factor (kg CO_2eq)	Data source (Ecoinvent database)
Copper oxide	kg	1,94	Althaus et al. (2007)
Sulphur	kg	1,39	Althaus et al. (2007)
Iron yarns	kg	1,48	Classen et al. (2009)
Diesel for farming (fuel production)	kg	0,51	Jungbluth (2007)
Diesel for farming (fuel combustion)	kg	3,1	Nemecek and Kagi (2007)
Italian energetic mix	kWh	0,65	Dones et al. (2007)
Yeast and nutrients for the yeast	g	0,001	Jungbluth et al. (2007)
Sulphur dioxide	g	0,0004	Althaus et al. (2007)
Glass bottle	kg	0,67	Hischier (2007)
Cork	g	0,001	Kellenberger et al. (2007)
Polyvinyl chloride (PVC)	g	0,003	Plastics Europe (2005)
Recycled paper, with deinking	g	0,002	Hischier (2007)
Recycled corrugated board	g	0,001	Hischier (2007)
Aluminum	kg	0,84	Classen et al. (2009)
Kraft paper bleached	kg	0,84	Hischier (2007)
High-Density-Polyethylene (HDPE)	kg	1,93	Hischier (2007)
Transport van < 3,5 t	tkm	1,9	Spielmann et al. (2007)
Transport lorry 3,5–20 t	tkm	0,28	Spielmann et al. (2007)

Table 4
Life cycle inventory for the field phase.

Field phase	Quantity per FU_{ha}	Quantity per FU_{Bottle}	Type of data	Data source
Copper oxide	1,75 kg	0,88 g	Primary	Farm registry
Sulphur	1,60 kg	0,8 g	Primary	Farm registry
Iron yarns	1,78 kg	0,89 g	Primary	Invoices
Organic fertilization (compost)	4 tons	2 kg	Primary	Directly measured (fresh weight)
Fuel consumption	212 L	89 g	Primary; Secondary	Farm registry; Specific weight of diesel 0,84 kg/L (Nemecek and Kagi, 2007)
Packaging of copper oxide and sulphur (paper)	15 g	0,008 g	Primary	Directly measured

Table 5
Life cycle inventory for the transformation process (vinification, bottling and packaging).

Transformation process	Quantity per FU_{ha}	Quantity per FU_{Bottle}	Type of data	Data source
Electricity (IT energy mix)	990 kWh	0,5 kWh	Primary	Invoices
Yeast and nutrients for the yeast	0,6 kg	0,30 g	Primary	Farm registry
Sulphur dioxide	0,3 kg	0,15 g	Primary	Farm registry
Packaging of yeast and nutrients (aluminum)	12 g	0,006 g	Primary	Directly measured
Packaging of sulphur dioxide (plastic HDPE)	15 g	0,008 g	Primary	Directly measured
Glass bottle	720 kg	360 g	Primary	Directly measured
Frontal and back labels (recycled paper)	5 kg	2,5 g	Primary	Directly measured
Cork	9 kg	4,5 g	Primary	Directly measured
Cap seal (plastic PVC)	1,6 kg	0,8 g	Primary	Directly measured
Cardboard box – for six bottles (recycled paper)	92 kg	46 g	Primary	Directly measured
Secondary packaging (plastic HDPE, paper) of the primary packaging	600–20 g	0,3–0,01 g	Primary	Directly measured

Table 6
Life cycle inventory for the transport of raw materials, fuel and packaging.

Type of transport	From	To	Type of vehicle	Distance (km)
Grape	field	cellar	tractor and trailer	0,6
Fuel	regional storage	field	lorry 3,5–20 t	45
Copper oxide, sulphur, iron yarns	regional storehouse	field	van<3,5 t	40
Yeast and nutrients for the yeast, sulphur dioxide	regional storehouse	cellar	van<3,5 t	65
Glass bottles	regional storehouse	cellar	lorry 3,5–20 t	60
Frontal and back labels	regional storehouse	cellar	van<3,5 t	40
Corks	regional storehouse	cellar	lorry 3,5–20 t	500
Cap seals	regional storehouse	cellar	lorry 3,5–20 t	200
Cardboard boxes	regional storehouse	cellar	lorry 3,5–20 t	55

and is provided by the national energy network with the average Italian energy mix. According to (Dones et al., 2007) an emission factor of 650 g CO_2eq is assigned per kWh of consumed electricity derived by the Italian energy mix at medium voltage.

During the vinification process 40 g of yeast and nutrients for the yeast are used per 100 L of wine for the fermentation and 20 g of sulphur dioxide are added per 100 L of wine for the preservation of wine during time. The bottling is carried out directly in the cellar and the final packaging is an ultra-light glass bottle of 0,75 L, with a frontal and back label in recycled paper, a cork and a plastic cap seal in polyvinyl chloride (PVC), usually commercialized in recycled cardboard boxes with six bottle each (Table 5).

The production, packaging and transport of raw materials, such as the yeast and the nutrients for the yeast, the sulphur dioxide, the glass bottles, the recycled paper labels, the corks, the cap seals and the recycled cardboard boxes were also included in this phase (Tables 5 and 6). No detergents are used in the cellar as the cleaning process is carried out with an innovative technology based on the use of ozone. This technology consists in the production of ozone directly from the oxygen of the air through an electrical input, already accounted in the total energy consumption of the cellar. Then, the ozone comes back to the air as oxygen after some minutes, thus avoiding the production of waste water.

As for the vineyard, a mass allocation method was applied also to GHG emissions of raw materials used in the transformation process. The GHG emissions of the packaging of yeast and nutrients (aluminum) and of sulphur dioxide (plastic: High-Density-Polyethylene - HDPE), and of the secondary packaging (plastic HDPE, paper) used in the transport of the single components of the primary packaging of the wine (glass bottles, recycled paper labels, corks, cap seals), as well as of the six-bottle cardboard box (recycled paper) were allocated in relation to the amounts needed for the production of $1FU_{bottle}$.

4. Results and discussion

4.1. Biogenic fluxes of GHGs of the vineyard system

The annual NEE of the sustainable vineyard system measured using the EC technique ($F_{CO2(EC)}$) was -150 g C m^2 $year^{-1}$ corresponding to $-5,5 \pm 0,5$ Mg CO_2eq ha^{-1} $year^{-1}$, with a range between $-4,97$ and $-6,04$ Mg CO_2 ha^{-1} included in the 5th and 95th percentile of the distribution (Table 7), which means a net annual carbon uptake by the ecosystem from the atmosphere.

The seasonal trend of NEE (Table 7, Fig. 2) shows a net carbon sink with a carbon accumulation starting already before the

Table 7
Monthly biogenic vineyard system–atmosphere net ecosystem exchange (NEE) measured with Eddy Covariance technique (g C m^2). Positive (+) sign indicates an emission while negative (−) sign indicates a sink.

Period		NEE (g C m^2)		
		50th percentile	5th percentile	95th percentile
2014	August	−19,91	−19,09	−22,09
	September	3,82	4,09	3,27
	October	8,73	9,00	7,64
	November	13,64	15,00	12,00
	December	−0,27	4,09	−0,55
2015	January	−1,36	−1,09	−1,91
	February	−11,73	−9,82	−12,00
	March	−21,00	−19,64	−21,55
	April	−24,82	−24,27	−25,09
	May	−23,45	−22,64	−25,09
	June	−30,55	−28,64	−34,09
	July	−43,09	−42,55	−45,27
Annual NEE (g C m^2)		**−150,00**	**−135,55**	**−164,73**
Annual NEE (Mg CO_2 ha^{-1})		**−5,50**	**−4,97**	**−6,04**

Table 8
Anthropogenic GHG emissions determining the CF assessed via LCA from the vineyard to the bottle of wine.

Life cycle phase			Mg CO_2eq per ha	kg CO_2eq per bottle (0,75L)
Agricultural phase	Diesel for farming	Fuel production and consumption for field operations	0,23	0,12
	Raw materials	Plant protection products (copper oxide, sulphur)	0,01	0,003
		Yarns for binding (iron, pvc)	0,004	0,002
	Packaging of raw materials	Packaging of plant protection products (paper)	0,0001	0,00004
	Transport[a]	Transport of raw materials	0,002	0,001
Total sustainable cultivation and management of the vineyard (15%)			0,24 ± 0,05	0,12 ± 0,03
Transformation process	Raw materials	Yeast, nutrients, sulphur dioxide, etc.	0,001	0,0004
	Packaging of raw materials	Packaging of raw materials (plastic HDPE, aluminum)	0,07	0,03
	Transport[a]	Transport of raw materials	0,0001	0,00004
	Electricity	IT energy mix	0,65	0,32
Total vinification and bottling phase (39%)			***0,72 ± 0,14***	***0,36 ± 0,07***
	Primary packaging	Glass bottle (ultra-light)	0,48	0,24
		Cork	0,01	0,01
		Cap seal (pvc)	0,01	0,003
		Frontal and back label (recycled paper)	0,01	0,004
		Cardboard (recycled paper) box containing 6 bottles	0,09	0,05
	Transport[a]	Transport of primary packaging	0,02	0,01
	Secondary packaging	Packaging for transport (plastic HDPE, paper)	0,001	0,001
Total wine packaging (46%)			***0,61 ± 0,12***	***0,31 ± 0,06***
Total transformation process in the cellar (85%)			**1,33 ± 0,27**	**0,67 ± 0,14**
Total CF			**1,57 ± 0,27**	**0,79 ± 0,14**

Note: uncertainties values are derived assuming an average variation of 20% of the uncertainty of the emission factors, as reported in the references listed in Table 3.
[a] The GHG emissions from the transport has been based on the distance travelled and the load of the truck including an empty return trip.

budbreak due to the increased activity of the grass cover, with a peak during the summer when the vine canopy is fully developed. The carbon accumulation was lower and turned into a slight emission in concurrence with the grape harvest, when the vines started their dormancy with leaf senescence and fall. These results confirm the carbon sink activity due to no-till and to the presence of grass cover under the vineyard, as observed also by Gianelle et al. (2015), Longbottom and Petrie (2015) and Marras et al. (2015). Therefore, these findings highlight the positive effect of such sustainable practices able to contribute to climate change mitigation allowing the system to act as carbon sink. Compared to other vineyard systems, the annual net carbon accumulation found in this study is in the range of mean values found in literature from 3 to 8 Mg CO_2eq ha^{-1} $year^{-1}$ (Chiriacò and Valentini, 2015; Gianelle et al., 2015; Marras et al., 2015; Brunori et al., 2016; Meggio and Pitacco, 2016; Scandellari et al., 2016; Morandé et al., 2017). However, the annual net carbon accumulation found in this study could also be even higher if considering the unfavorable weather conditions that in 2014 reduced the vines' productivity (as discussed in section 2). In this regard, in fact, some studies report annual net carbon accumulation in vineyard systems that can reach even values around 30 Mg CO_2eq ha^{-1} $year^{-1}$ (Guo et al., 2014; Chiriacò and Valentini, 2015; Gianelle et al., 2015). Hence, the results of this study confirm that sustainably managed vineyard systems could act as carbon sink thanks to their aptitude to sequester carbon in their permanent woody structures and in soils, even if the magnitude could depend on annual climate conditions.

On the other side, the crop residue management for the production of compost and its application to the soil imply a certain amount of biogenic GHG emissions (IPCC, 2006). The emissions from crop residue fermentation for the production of compost have been included in this budget for complete assessment, despite they would have probably been produced also in case the residues were landfilled, even with a higher rate according with Lou and Nair (2009). The CO_2 emissions due to the aerobic fermentation during the compost production ($F_{CO2(C)}$) were assessed to be 1,25 ± 0,1 Mg CO_2 ha^{-1}. The CH_4 and N_2O emissions from the compost production process ($F_{CH4(C)}$ and $F_{N2O(C)}$) were 0,45 ± 0,4 Mg CO_2eq ha^{-1} and 0,26 ± 0,29 Mg CO_2eq ha^{-1}, respectively. Soil emissions of N_2O due to the compost application for soil

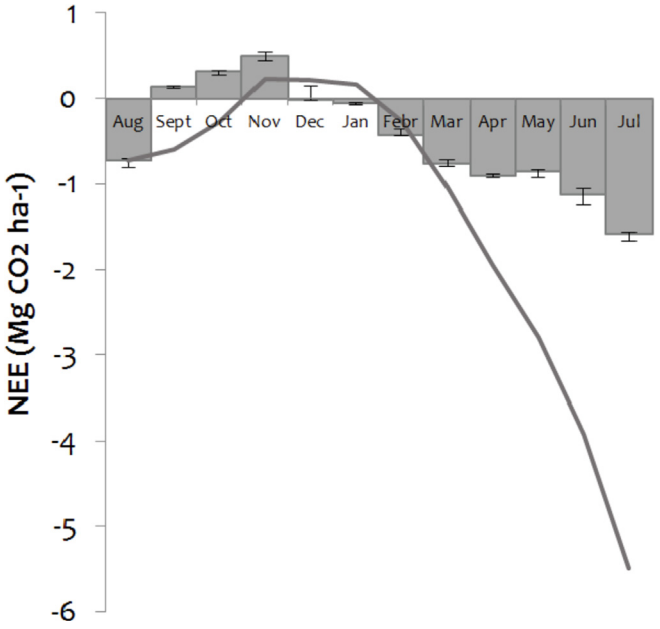

Fig. 2. Monthly vineyard–atmosphere net ecosystem exchange (NEE) of biogenic fluxes of CO_2 measured with Eddy Covariance technique (Mg CO_2 ha^{-1}). Positive (+) sign indicates an emission while negative (−) sign indicates a sink. The vertical bars indicate the distribution between the 5th and the 95th percentile. The continuous line shows the carbon accumulation (expressed in Mg CO_2 ha^{-1}) as sum of the monthly fluxes.

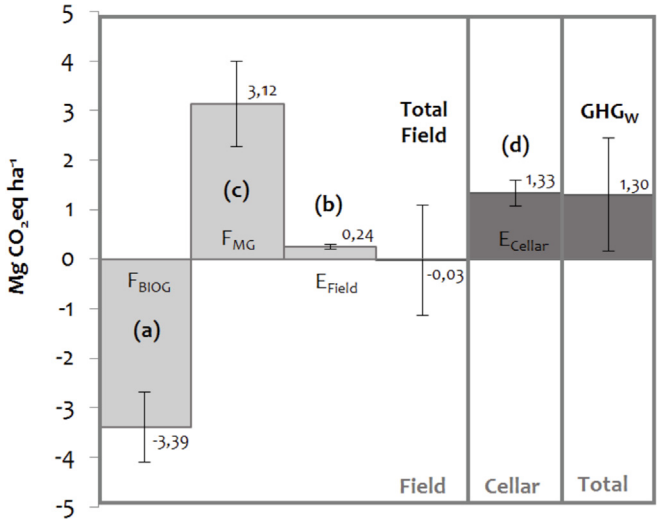

Fig. 3. The GHG budget from the vineyard system up to the wine production (GHG_W), calculated as the sum of the (a) biogenic vineyard–atmosphere fluxes of greenhouse gases (F_{BIOG}), the (c) annual carbon stock changes in the vineyard due to the agronomic operations in the field (F_{MG}), and the (b + d) anthropogenic emissions of greenhouse gases due to the management of the overall life cycle from the vineyard to the bottle of wine (E_{Field} and E_{Cellar}). Positive (+) sign indicates an emissions into the atmosphere, while a negative (−) sign represents an uptake from the atmosphere. The vertical bars indicate the uncertainty range.

fertilization ($F_{N2O(S)}$) were estimated to be 0,15 ± 0,02 Mg CO_2eq ha^{-1} (Table 9).

Therefore, the overall budget of the biogenic GHG fluxes of the system resulted in a net annual sink of −3,39 ± 0,71 Mg CO_{2eq} ha^{-1} (Table 9, Fig. 3).

4.2. Annual carbon stock changes due to the agronomic management

The annual carbon stock change due to the agronomic operations applied for the management of the vineyard, that includes the pruning of biomass, the grape harvesting and the compost application, resulted in a net GHG emission of 3,12 ± 0,85 Mg CO_2eq ha^{-1} (Table 9, Fig. 3).

In particular, in 2014–2015 the total amount of pruned biomass in the vineyard was 3,1 ± 0,76 tons per hectare (fresh weight), with a net carbon loss from the vineyard system corresponding to a GHG emission of 2,88 ± 0,71 Mg CO_2eq ha^{-1} (F_{PB}). Moreover, the GHG emissions corresponding to the carbon removed by the system with the harvest of the grape (F_G) resulted to be 1,23 ± 0,25 Mg CO_2eq ha^{-1}. Those emissions are calculated from the carbon contained both in the grape juice (1.500 liters ha^{-1}), corresponding to 0,92 Mg CO_2eq ha^{-1} and including emissions released as part of the wine fermentation process, and in the 0,9 tons ha^{-1} of grape residues resulting from the vinification process, corresponding to 0,31 Mg CO_2eq ha^{-1} (Table 9).

On the other side, the application under the rows of the on-farm compost produced from crop residues as soil fertilizer implies a return to the vineyard of a fraction of the organic carbon previously subtracted with the grape harvest and the pruning of biomass. In fact, part of the organic carbon content of the compost applied to the soil is lost through the respiration process and already included

Table 9
Annual GHG budget of the sustainable grape-to-wine system. Positive sign (+) represents an emission and negative sign (−) represents a sink.

GHG budget (GHG_W)		Method for the assessment	Mg CO_2eq per hectare	kg CO_2eq per bottle
(a) Biogenic fluxes of GHGs of the vineyard system:				
CO_2 fluxes	$F_{CO2(EC)}$	EC technique	−5,50 ± 0,5	−2,75 ± 0,3
CO_2 from compost production	$F_{CO2(C)}$	IPCC (2006)	1,25 ± 0,1	0,62 ± 0,05
CH_4 from compost production	$F_{CH4(C)}$	IPCC (2006)	0,45 ± 0,4	0,23 ± 0,2
N_2O from compost production	$F_{N2O(C)}$	IPCC (2006)	0,26 ± 0,29	0,13 ± 0,15
N_2O from soil management	$F_{N2O(S)}$	IPCC (2006)	0,15 ± 0,02	0,07 ± 0,01
Total F_{BIOG}			**−3,39 ± 0,71**	**−1,7 ± 0,36**
(c) Carbon stock changes due to the agronomic management:				
SOC stock change from compost application	F_S	Data from literature	−0,99 ± 0,44	−0,5 ± 0,2
Carbon loss due to grape harvest	F_G	Direct measure	1,23 ± 0,25	0,62 ± 0,13
Carbon loss due to pruning of biomass	F_{PB}	Direct measure	2,88 ± 0,71	1,44 ± 0,35
Total F_{MG}			**3,12 ± 0,85**	**1,56 ± 0,43**
Anthropogenic GHG emissions:				
(b) GHG emissions from field operations	E_{Field}	LCA	0,24 ± 0,05	0,12 ± 0,03
(d) GHG emissions from transformation	E_{Cellar}	LCA	1,33 ± 0,27	0,57 ± 0,14
Total E_{ANTR}			**1,57 ± 0,27**	**0,79 ± 0,14**
Total GHG_W			**1,30 ± 1,14**	**0,65 ± 0,57**

in the EC measures, while another part is assumed to be transferred to the SOC pool, with a long-term carbon stabilization leading to an annual increase of the SOC content (Favoino and Hogg, 2008; Sánchez-Monedero et al., 2015). Many studies in literature demonstrate that sustainable agricultural practices such as organic farming or the application of organic fertilizer can potentially sequestrate more carbon in the soils and thus convert the soils to a net carbon sink (Gregorich et al., 2007; Gattinger et al., 2012; Lynch et al., 2011). However, the annual SOC increase due to the compost application should be assessed as mean annual value of at least a twenty-year trend (IPCC, 2006; Chiti et al., 2018). Therefore, in absence of a such time series data, average values from existing literature were considered. Bos et al. (2017) modelled a mean SOC increase of 0,32 t C ha^{-1} $year^{-1}$ across a 25-year period of compost application, while Triberti et al. (2008) founded 0,16 t C ha^{-1} $year^{-1}$. Freibauer et al. (2004) suggest a potential SOC sequestration rate of 0,4 t C ha^{-1} $year^{-1}$ and a carbon sequestration of approximately 50 kg per ton of wet compost is reported by Lou and Nair (2009). From these values found in literature, the average annual rate of SOC increase due to the annual compost application was assumed to be $0,27 \pm 0,1$ Mg C ha^{-1} corresponding to a net annual CO_2 removal of $-0,99 \pm 0,4$ Mg CO_2eq ha^{-1}. Thereby, the sustainable practice of on-farm compost application, besides representing an alternative to the use of synthetic fertilizers, thus avoiding the GHG emissions and other environmental impacts due to their production and use, contribute also to climate change mitigation with a significant increase in soil carbon sequestration.

4.3. Anthropogenic GHG emissions from vineyard management and transformation process

The anthropogenic GHG emissions resulting from the LCA analysis were $1,57 \pm 0,27$ Mg CO_2eq ha^{-1} (Table 8) considering both the sustainable agricultural phase in the vineyard (responsible of an emission of $0,24 \pm 0,05$ Mg CO_2eq ha^{-1}) and the transformation process of the grape into wine, including vinification, bottling and packaging (responsible of an emission of 1,33 Mg CO_2eq ha^{-1}).

As observed by Chiriacò et al. (2017), and previously reported in paragraph 3.3, the CF assessed per unit of land (FU_{ha}), besides that per unit of product, allow a more comprehensive assessment of the real contribution to climate change especially for food products and agricultural areas where agronomic practices can influence the organic carbon content in soils and/or in woody perennial biomass. However, several studies in literature still assess the carbon footprint solely per unit of product. Thus, in order to allow any kind of comparison of results with other studies in literature, both FUs per unit of land (FU_{ha}) and per unit of product (FU_{Bottle}) have been assessed. Therefore, considering the number of bottles of wine produced per unit of area, that is of 2.000 bottles of 0,75 L per hectare, the carbon footprint of a bottle of wine is $0,79 \pm 0,14$ kg CO_2eq $bottle^{-1}$ (Table 8). The CF found in this study is consistent with the results obtained from other studies in literature that range on average between 0,6 and 1,6 kg CO_2eq $bottle^{-1}$ (Ardente et al., 2006; Gazulla et al., 2010; Bosco et al., 2011; Benedetto, 2013; Vázquez-Rowe et al., 2012b; Fusi et al., 2014) with some studies that report also higher values up to 3,2 kg CO_2eq $bottle^{-1}$ (Vázquez-Rowe et al., 2012a; Neto et al., 2013). Diverse results in literature depend on different use of inputs and agronomic management under specific pedo-climatic conditions or by particular features of the transformation process or packaging characteristics. Also the boundaries of the analyzed system and the phases included in the analysis may provide differences in the estimate of the emissions. In fact, while almost all the studies in literature analyze the CF including the agricultural phase, the transformation process (vinification, bottling and packaging), some include also the vine planting phase and some others the distribution phase. The findings of this study, that encompasses the agricultural phase and the transformation process (including vinification, bottling and packaging), show a low value of total CF respect to average values in literature, thus demonstrating the sustainability of the analyzed wine making process with a low contribution to climate change in terms of anthropogenic GHG emissions. Moreover, the CF found in this study could also be even lower if considering the unfavorable weather conditions that in 2014 reduced the vines' productivity (as discussed in section 2).

Table 8 reports the CF per unit of area (FU_{ha}) and per unit of product (FU_{Bottle}) and shows the contribution of each phase in terms of anthropogenic GHG emissions assessed with the LCA approach. The agricultural phase for the sustainable cultivation and management of the vineyard is responsible for the 15% of the anthropogenic emissions, corresponding to $0,24 \pm 0,05$ Mg CO_2eq ha^{-1} when considering the unit of cultivated land (FU_{ha}) and to $0,12 \pm 0,03$ kg CO_2eq $bottle^{-1}$ when considering the unit of product (FU_{Bottle}). The transformation phase of grape into wine, including the vinification, the bottling and the final packaging, is responsible for the remaining 85% of the anthropogenic emissions, with $1,33 \pm 0,27$ Mg CO_2eq ha^{-1} or $0,67 \pm 0,14$ kg CO_2eq $bottle^{-1}$, of which the contribution attributable to the final packaging of the bottle of wine is $0,61 \pm 0,12$ Mg CO_2eq ha^{-1} or $0,31 \pm 0,06$ kg CO_2eq $bottle^{-1}$, corresponding to 46% of the total anthropogenic GHG emissions.

The main existing literature on CF of the wine making process shows that the agricultural phase contributes from 16% up to 40% (Bosco et al., 2011; Point et al., 2012; Vázquez-Rowe et al., 2012a; Benedetto, 2013; Neto et al., 2013; Rugani et al., 2013; Fusi et al., 2014; Bartocci et al., 2017) to the anthropogenic GHG emissions, with some studies showing that viticulture is one of the highest impacting phases of the wine life cycle (Vázquez-Rowe et al., 2012a; Neto et al., 2013; Ferrara and De Feo, 2018).

The results of the LCA applied in this study show a lower contribution of the agricultural phase (15%) in sustainable viticulture to the total CF, with the main contribution within this phase represented by the fossil fuel consumption for the machinery used in the field (Table 8). The sustainability of the agricultural phase in this study is confirmed also as absolute value, both per unit of land with $0,24 \pm 0,05$ Mg CO_2eq ha^{-1} and per unit of product with only $0,12 \pm 0,03$ kg CO_2eq $bottle^{-1}$ against values found for viticulture in literature ranging from 0,33 to 0,80 and even to 2,5 kg CO_2eq $bottle^{-1}$ (Gazulla et al., 2010; Bosco et al., 2011; Point et al., 2012; Vázquez-Rowe et al., 2012a; Neto et al., 2013). The minor anthropogenic GHG emissions of the agricultural phase, respect to average values in literature, are due to the low level of inputs in sustainable viticulture that excludes the use of chemicals for fertilization and uses a limited amount of plant protection products (copper and sulphur in the limit allowed by the regulation for organic farming). In fact, the compost application to the vineyard system substitutes the use of synthetic fertilizers, thus avoiding the GHG emissions and other environmental impacts due to their production and use. These findings are confirmed also by other studies that observed that the main sources of emissions within the agricultural phase in viticulture are mainly due to the fossil fuel consumption for the agricultural operations and to the use of fertilizers and pesticides that generate high polluting emissions both during their production and their subsequent application in the field (Notarnicola et al., 2003; Aranda et al., 2005; Ardente et al., 2006; Niccolucci et al., 2008; Pizzigallo et al., 2008; Gazulla et al., 2010; Bosco et al., 2011; Point et al., 2012; Benedetto, 2013; Neto et al., 2013; Rugani et al., 2013; Fusi et al., 2014; Marras et al., 2015; Litskas et al., 2017; Ferrara and De Feo, 2018). Therefore, the results of the study demonstrate that sustainable viticulture is a low-carbon

agriculture with a lower contribution to climate change in terms of anthropogenic GHG emissions per hectare (or per bottle), as demonstrated also for precision viticulture by Balafoutis et al. (2017).

In the transformation process the main contribution of anthropogenic GHG emissions is provided by the energy consumption for the electricity used for machineries and the temperature control in the cellar, that accounts for 49% of the transformation emissions with 0,32 kg CO_2eq bottle^{-1} (Table 8), followed by the glass bottles that accounts for 36% of the transformation emissions with 0,24 kg CO_2eq bottle^{-1} (Table 8). The share of these two main contributors within the transformation phase is confirmed also by Iannone et al. (2016) and Martins et al. (2018) although the absolute values of the CF of these two phases in the analyzed sustainable wine making process are lower. The minor anthropogenic GHG emissions of the transformation process and packaging phase, respect to average values in literature, are due to the reduced use of energy for electricity in the cellar taking advantages from the natural damping of the outside temperature of the cellar that is dug into the rock and to the use of ultralight glass bottle (suggested also by Martins et al. (2018) as a strategy to reduce GHG emissions) that weigh 10% less than conventional wine bottles leading to lower emissions for their production and transport.

Thus, these findings demonstrate that sustainable practices both in viticulture and in the transformation phase, can have a low contribution in terms of GHG emissions, both per unit of land (FU_{ha}) and per unit of product (FU_{Bottle}).

4.4. Combined analysis for a comprehensive greenhouse gas budget

Fig. 3 shows the diverse components of the overall GHG budget (assessed with Eq. (1)) in relation both to the agricultural phase in the field and to the transformation process in the cellar. In particular, the GHG emissions and removals occurring in the field include the (a) biogenic GHG fluxes and the (b) anthropogenic GHG emissions generated for the grape production as well as the (c) carbon stock change due to the vineyard management. Then, for a complete assessment of the full grape-to-wine system, also the (d) GHG emissions generated by the grape transformation process into wine are considered.

As previously reported, the main contribution in terms of uptake of carbon from the atmosphere is provided by the biogenic CO_2 vineyard system–atmosphere fluxes measured with the EC technique, that registered an average net annual sink of $-5,5 \pm 0,05$ Mg CO_2 ha^{-1} year^{-1} in 2014–2015 ($F_{CO2(EC)}$, see Table 9). As discussed in section 4.1, these results confirm the role of the vineyard system of carbon sink thanks to its aptitude to sequester carbon in the permanent woody structures and in the soil enhanced by the sustainable agronomic practices of no-till and the presence of grass cover (Gianelle et al., 2015; Longbottom and Petrie, 2015; Marras et al., 2015). These findings demonstrate the positive effect of such sustainable practices that revealed to be able to increase the carbon sink of the vineyard, thus contributing to climate change mitigation.

Nevertheless, this positive budget in terms of carbon sink is reduced by the annual carbon stock change due to the grape harvest and the pruning of biomass that is shredded and removed from the vineyard system as a strategy to avoid the spread of pests and diseases thus strongly reducing the use of chemicals for pests' control. The amount of carbon removed by the grape harvest and the pruning of biomass corresponded respectively to $1,23 \pm 0,25$ and $2,88 \pm 0,7$ Mg CO_2eq ha^{-1} year^{-1} (F_G and F_{PB} in Table 9). However, the vineyard resides (pruned biomass + grape resides) are collected for the production of compost to be used on-farm as organic fertilizer of soil. In this way the carbon subtracted with the removal of grape and pruned biomass is then in part reallocated to the vineyard system through the compost application to soil. The amount of carbon that is assumed to be reallocated to the soil corresponds to $-0,99 \pm 0,4$ Mg CO_2eq ha^{-1} year^{-1} (F_S in Table 9), at the net of the CO_2, CH_4 and N_2O generated by the compost fermentation that accounted for a total GHG emission of $1,96 \pm 0,5$ Mg CO_2eq ha^{-1} year^{-1} (sum of $F_{CO2(C)}$, $F_{CH4(C)}$ and $F_{N2O(C)}$ in Table 9) and of the CO_2 soil respiration following the compost application already included in the EC measures. For a comprehensive assessment also the final N_2O emissions from the soil due to the compost application has been subtracted to the total GHG budget, corresponding to $0,15 \pm 0,02$ Mg CO_2eq ha^{-1} year^{-1} ($F_{N2O(S)}$ in Table 9).

Thus, if including only the (a) biogenic GHG fluxes (F_{BIOG}) of $-3,39 \pm 0,71$ Mg CO_2eq ha^{-1} year^{-1} and the (c) carbon stock changes due to the agronomic management (F_{MG}) of $3,12 \pm 0,85$ Mg CO_2eq ha^{-1} year^{-1}, the GHG budget of the sustainable vineyard system results to be a positive sink of carbon equivalent to $-0,27 \pm 1,11$ Mg CO_2eq ha^{-1} year^{-1} that can be considered as the potential carbon sink of a unit of land (hectare) of a sustainably managed vineyard (Fig. 3). This positive result in terms of carbon sink is mainly due to sustainable practices such as the no-till and grass cover in the vineyard and the application of compost derived by the vineyard residues, that lead to a significant increase in carbon sequestration by the system. Therefore, these findings show as sustainable viticulture can be a low-carbon agriculture with a potential to even contribute to climate change mitigation in terms of carbon sink with a contribution per unit of managed land of $0,27 \pm 1,11$ Mg CO_2eq ha^{-1} year^{-1}.

Despite these findings come from a local wine production in Italy, if sustainable practices are extended to the global area covered by vineyards in the world, that is approximatively 7 Mha, it can be inferred that the total potential contribution in terms of carbon sink of viticulture could reach about 1,9 million tons of CO_2eq year^{-1} at global level, depending however by local conditions. Similar considerations on sustainable agriculture, that is currently applied on a total of 453 Mha of agricultural land (9% of worldwide total), are reported by Mayer et al. (2018) and Pretty et al. (2018).

Moreover, if considering also the (b) anthropogenic GHG emissions of the field operations for the sustainable management of the vineyard, that accounted for $0,24 \pm 0,05$ Mg CO_2eq ha^{-1} year^{-1} (E_{Field} in Table 9), the overall GHG budget at the vineyard level tends to be close to zero (Fig. 3), showing a potential carbon neutrality of sustainable viticulture.

The sustainable transformation process (including vinification, bottling and packaging) still remains a source of GHG emissions (d) of $1,33 \pm 0,27$ Mg CO_2eq ha^{-1} year^{-1} (Fig. 3), albeit sensibly reduced respect to average values in literature.

Hence, what is clear is that, as discussed in section 4.3, the sustainable management of the vineyard leads to a general low contribution to climate change in terms of anthropogenic GHG emissions per hectare or per bottle of wine. This is mainly due to a minor use of inputs, with particular regard to the use of agrochemical compounds for fertilization and plant protection. The lower contribution to climate change in terms of anthropogenic GHG emissions occurs also in the transformation process in the cellar. The reduced use of energy for electricity thanks to the natural temperature control in the cellar that is dug into the rock and the use of ultralight glass bottle with 10% of glass less than conventional wine bottles result in minor GHG emissions per hectare or per bottle of wine.

Therefore, this study shows that sustainable viticulture and wine making process have in general a lower contribution to climate change in terms of anthropogenic GHG emissions per

hectare or per bottle of wine. Moreover, the results demonstrate also that sustainable viticulture is a low-carbon agriculture that can turn the agrosystem into a net carbon sink able to totally compensate anthropogenic GHG emissions generate from the field (Fig. 3), allowing food production with a potential carbon neutrality without contributing to exacerbate climate change.

Hence, sustainably viticulture can lead to beneficial effects to climate change both in terms of enhanced capacity to capture carbon from the atmosphere and in terms of reduced anthropogenic GHG emissions for the management, while ensuring food production. The overall benefit of sustainably managed viticulture systems demonstrated in this study is related to the capacity to be a positive carbon sink so to even compensate the anthropogenic GHG emissions generated from the field operations, leading to a carbon neutral agrosystem.

5. Conclusion

Sustainable agriculture is recognized as the pathway to address climate change adaptation and mitigation while ensuring food production to feed the current human population and the expected 9.8 billion by 2050 (FAO, 2017; UN, 2017). In this sense, this study shows that sustainable agricultural practices applied to viticulture lead to a low-carbon agrosystem, with a lower contribution to climate change in terms of GHG emissions per hectare (or per bottle). The minor use of inputs, with particular regard to the use of agrochemical compounds for fertilization and plant protection, the reduced use of energy for electricity in the cellar and the use of ultralight glass bottle make the wine making process sustainable with lower GHG emissions.

On the other side, vineyard systems could act as carbon sink thanks to their aptitude to sequester carbon in their permanent woody structures and in soils, enhanced by sustainable practices as no-till and the presence of grass cover. Also the application of compost obtained from vineyard residues in substitution of the use of synthetic fertilizers reduces the use of inputs and related GHG emissions, contributing to climate change mitigation, with a significant increase in soil carbon sequestration.

These findings confirm the positive effect of sustainable practices applied to viticulture and highlight their potential to even turn the agrosystem into a net carbon sink able to totally compensate anthropogenic GHG emissions generated for the field management, leading to a carbon neutral agrosystem, thereby contributing to climate change mitigation. The sustainable transformation process still remains a source of GHG emissions, albeit sensibly reduced respect to average values in literature.

A such kind of assessment of the GHG budget of sustainable viticulture can provide also useful information for the monitoring of the effect on climate change of sustainable practices applied for example in the framework of national adaptation or mitigation plans and in the context of the CAP. Moreover, the assessment on GHG budget of viticulture provided in this study is useful also for the reporting and accounting of emissions and removals in the LULUCF and agriculture sectors in the framework of the UNFCCC and the second commitment period of the Kyoto Protocol (2014–2020) as well as under the commitments foreseen by the Reg. UE 529/2013 for the reporting of emissions and removals of cropland management.

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